Cathode Rays

BY JOSEPH JOHN THOMSON, D.Sc., F.R.S.,

With special reference to recent investigations by the author, Professor of Experimental Physics, Cavendish Laboratory, Cambridge, England

THE study of the effects which occur when a current of electricity passes through gas at a very low pressure has recently led to results having a very direct bearing on our ideas of matter and electricity. The phenomena known to physicists as the "cathode rays" have played such an important part in these developments that a short account of them may not be without general interest, especially as the phenomena are of singular beauty, and many of them can readily be observed by any one with access to the usual appliances for producing Röntgen rays.

When a current of electricity is sent between two wires fused in a glass tube from which the air has been exhausted until the air pressure is only an exceedingly small fraction, say one-ten-thousandth, of the atmospheric pressure, the tube presents a very striking and varied appearance, of which the general nature may be gathered from Figs. 1 and 2. Confining our attention to the neighborhood of the wire by which the current leaves the tube (this wire is called the cathode; it is the one marked — in the figure), we find (see Fig. 2) a velvety glow spreading over the surface of the wire; next to this comes a space called the dark space, which is almost dark, and whose boundaries run parallel to the surface of the wire forming the cathode; outside the dark space the gas is luminous for some distance, this luminous portion forming what is known as the negative glow.

So far we have been describing the appearance of the gas left in the tube, but the gas is not the only source of light, for the glass in the part of the tube near the cathode glows with a vivid phosphorescence, the color of which depends upon the kind of glass of which the tube is made. If the glass is soda glass, the light given out is a bright yellowish-green, while with lead glass the light is blue. It is to the cause of this phosphorescence that we wish to call attention in this article. This phosphorescent glow is a striking example of the important discoveries in physics which often immediately follow improvements in the apparatus; for it was Geissler's improvements in air-pumps, by which air could be much more efficiently extracted from the tubes, which led to the discovery of the glow on the glass, and rendered its investigation possible.

The study of the cause of the phosphorescence on the glass was commenced by Plücker in 1859, and carried on with great vigor by Hittorf (1869) and Goldstein (1876) in Germany, by Crookes (1879) in England, and by Puluj in Austria. It was soon found that the phosphorescence was produced by something coming from the neighborhood of the cathode, for a solid placed between the cathode and the walls of the tube cast a shadow on the tube; an example of this effect is shown in Fig. 3, where the shadow is caused by a Maltese cross made of mica (Fig. 3), placed between the cathode and the tube: the shape of the shadow shows that the cause of the phosphorescence travels in straight lines, and that these lines are, approximately at any rate, at right angles to the surface of the cathode, so that if the cathode is shaped like a bowl, there is a great concentration of the effect at the centre (Fig. 4). The name "cathode rays" for the agent producing the phosphorescence is due to Goldstein; and although now, in consequence of the universal acceptance of the undulatory theory of light, a ray is generally associated in the minds of physicists with an undulatory motion in the ether, this association is only accidental, and there is no necessary con-

nection between a ray and undulatory motion; indeed, Nelson uses the term in connection with his corpuscular theory of light, and the cathode rays, as we shall see, have an extraordinary resemblance to the conditions postulated in that theory for a ray.

The cathode rays have many very interesting properties. They heat up a body on which they fall, and by concentrating them by using a bowl-shaped cathode like that shown in Fig. 4, a piece of platinum foil may be raised to a white heat, glass melted, and even a diamond charred. Again, the rays, when they strike against an object, tend to push it away, the object behaving just as if it were struck by a stream of particles coming from the cathode. This is prettily shown in the experiment due to Sir William Crookes, represented in Fig. 5, when the impact of the rays makes the little carriage move from one end to the other of the rails. The phosphorescence of the glass of the tube is an example of a very general phenomenon, for very many substances when struck by the rays phosphoresce brightly, giving out a light peculiar to the substance: for example (Fig. 6), the rare earth yttria emits when exposed to these rays light having a peculiar citron band on its spectrum, and it was by the characteristic light given out under these rays that Sir William Crookes was able to study and isolate some of the rarer elements. Again, some substances, such as common salt, experience a peculiar change in color when exposed to these rays; crystals of rock-salt become a pretty violet-blue, looking almost like gems—the color is unfortunately somewhat fugitive if the crystals are exposed to a moist atmosphere. Some, however, in my possession, which have been kept dry, are still blue, although they are now nearly four years old. An even more subtle change is produced by the rays in some mixtures of salts, such as a mixture of sulphate of calcium with a little sulphate of manganese. This mixture is not altered in appearance by the rays, but for some time after its exposure it bursts into a vivid greenish glow when slightly heated; this effect, which was discovered by Professor E. Wiedeman, is called thermo-luminescence. Glass, too, is changed by a long exposure to the rays; it gets as it were tired, and loses to a considerable extent its powers of phosphorescing. A piece of tarnished copper is rapidly cleaned by the rays. They produce, too, a very remarkable change in the rarefied gas in the tube as they pass through it; for this gas, which, when the rays are not passing through it, is an insulator, becomes a conductor of electricity as soon as it is traversed by them; the path of the rays is marked by luminosity in the gas, and can thus be followed by the eye.

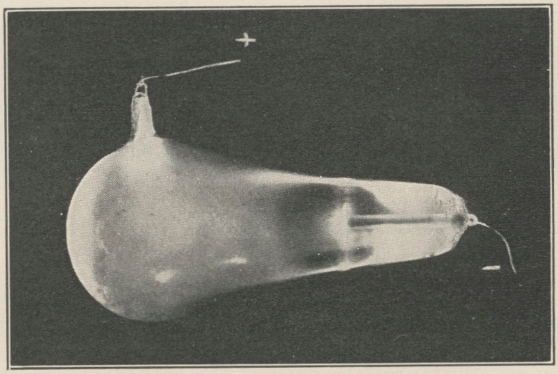

Fig. 1.—General Nature Of The Phenomenon

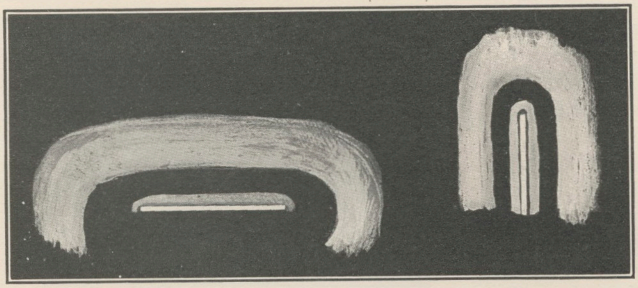

Fig. 2.—Showing The Cathode Wire

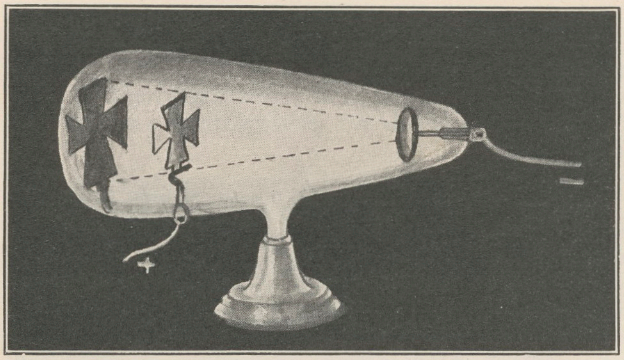

Fig. 3.—Illustrating Cause Of Phosphorescence On The Glass

By means of this luminosity, or by the phosphorescence on the glass, it can easily be proved that although under ordinary circumstances the path of the cathode rays is a straight line, it is not so when the rays are exposed to the action of a magnet; this makes the path curved, and bends it up or down, to one side or the other, according to the direction of the magnetic force. This effect is illustrated in Fig. 7, where the straight horizontal beam shows the path when there is no magnet near the rays, the curved beam the path when the rays travel between the poles of a horseshoe magnet, producing a magnetic force at right angles to the path of the ray: the bending of the rays is always at right angles to the magnetic force. A practical application, due to Braun, of the bending of the rays under magnetic force is coming into extensive use in electrical engineering, where it is sometimes necessary to study magnetic forces which are rapidly changing. Ordinary magnets are useless for this purpose, as they are much too heavy to follow the vagaries of the magnetic force, but the cathode rays, having practically no mass, are able to follow the changes in the force no matter how rapid they may be, and by watching the movements of the rays we can deduce the behavior of this force.

The most widely known property of the cathode rays is that of producing Röntgen rays; the cathode rays are the parents of the Röntgen rays, for the latter are produced whenever the cathode rays strike against a solid obstacle. The cathode and Röntgen rays have many points of resemblance; they both affect a photographic plate, they both cause substances against which they strike to phosphoresce, and they both make gas through which they pass a conductor of electricity. The cathode rays, too, as we shall see, have some power of penetrating opaque solids, though this is small compared with that possessed by the Röntgen rays; the essential differences between the two rays are that the Röntgen rays are not deflected by a magnet, nor by an electric force, nor do they carry with them a charge of electricity.

Physicists until three or four years ago were very much divided in opinion as to the nature of the cathode rays; the German physicists, with very few exceptions, held that these were something of the nature of waves in the ether, with which matter had nothing to do. The English physicists were, I think, unanimous in regarding the cathode rays as due to particles of gas charged with negative electricity, and projected with great velocity from the cathode: they pointed out how readily this view explained the mechanical and thermal effects produced by the rays, and their deflection by a magnet. Varley in 1870 seems to have been the first to suggest the occurrence of such particles in the electric discharge, though it is perhaps doubtful whether he was referring specifically to the cathode rays. The charged particles were used by Crookes to explain and co-ordinate the

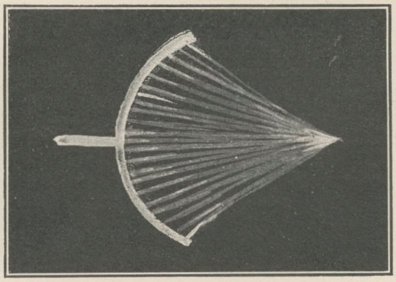

Fig. 4.—Concentration Of Cathode Rays

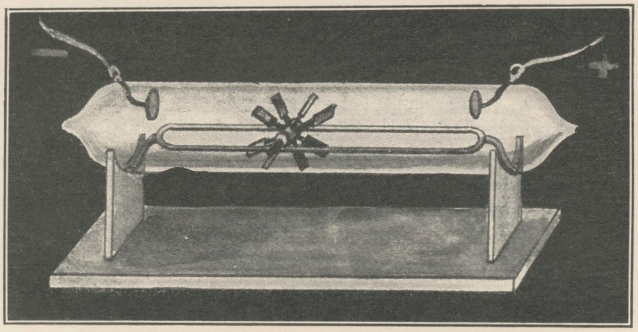

Fig. 5.—Cathode Rays Pushing Away An Object

very striking results obtained by him in his experiments on this subject.

Interest in this controversy was much stimulated by a discovery made by Hertz in 1892. Hertz showed that solids were not, as had been supposed, absolutely impenetrable by these rays; for he proved that the rays could pass through gold-leaf and produce phosphorescence on glass behind it. This seemed a formidable objection to the view that the cathode rays were charged particles, for though examples of the penetration of solids by gases are not wanting—for instance, hydrogen can readily pass through red-hot platinum, and even a liquid like water can be forced by great pressure through gold—yet Hertz's discovery was undoubtedly much more favorable to the ether view than to the particle one, as no person had suggested that these particles were other than the molecules or atoms of the gas in the tube. Hertz's result received a very beautiful extension by Lenard, who made a tube which had in it a small window of very thin aluminium foil. Shooting the cathode rays against this window, he found that they penetrated it and got outside the tube, where they could be much more easily investigated. Lenard was thus the first physicist to cross the Rubicon between the inside and the outside of the tube, and for this reason the cathode rays outside the tube are generally called Lenard rays.

From this time, however, all the evidence began to go in favor of the particle theory. In 1896 a young French physicist, M. Perrin, showed that the cathode rays carried a charge of negative electricity with them, and in 1897 the writer showed that they were deflected by an electric force just as if they were negatively electrified. After these results it could hardly be doubted that the cathode rays were really negatively electrified particles, and the difficulty in the way of this view, due to the penetration of solids by the rays, was explained by some experiments made by the writer in 1897, in which the masses of the charged particles, the charge carried by them, and their velocity were measured. These measurements showed that the particles in the cathode rays are not ordinary atoms or molecules at all, but something very much smaller, for the mass of each of these particles is only about one-thousandth part of that of the atom of hydrogen, the smallest mass hitherto recognized. Investigations made by Wiechert, Kaufmann, and Lenard have led to the same conclusion. Nor is this extreme smallness the only remarkable feature about these particles; for it was found that whatever might be the nature of the gas in the tube,

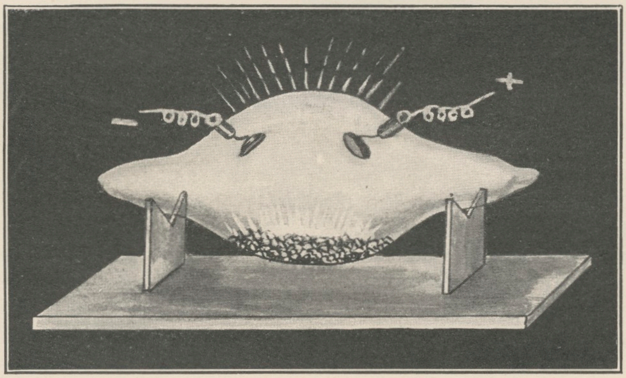

Fig. 6.—Phosphorescence Of Object Struck By Cathode Rays

or whatever metal was used for the cathode, the mass of the particles remained the same. Thus in these particles we have something possessing the properties of ordinary matter, having a definite mass, which is yet exceedingly small compared with the mass of any known element; the particles of this new kind of matter thus correspond to a very much finer state of subdivision than that of ordinary matter into its molecules. The speed with which these particles move is also a feature of great interest. These speeds have been measured, and are found to be so enormous that the velocity of the swiftest bullet is quite insignificant in comparison: the speed of the particles depends upon the electric force which can be applied to the tube, and this changes with the amount of gas left in it; but a particle which did not move with a velocity more than a thousand times that of the swiftest cannon ball, which is about two thousand miles per hour, would be one of the slowest of its species. The only velocity with which we can compare that of these particles is the velocity of light, which is about 186,000 miles per second—and cathode particles have been observed in the tube having a velocity as much as one-third of this. Thus in the tube near the cathode we have bodies smaller than atoms moving with prodigious velocities, a state of things which recalls Newton's corpuscular theory of light, according to which light consists of very small particles (corpuscles) moving at the rate of 186,000 miles per second. Although this theory of light has long since been abandoned, Newton's conception is realized in the cathode rays; and I have ventured to call the small particles which constitute these rays corpuscles.

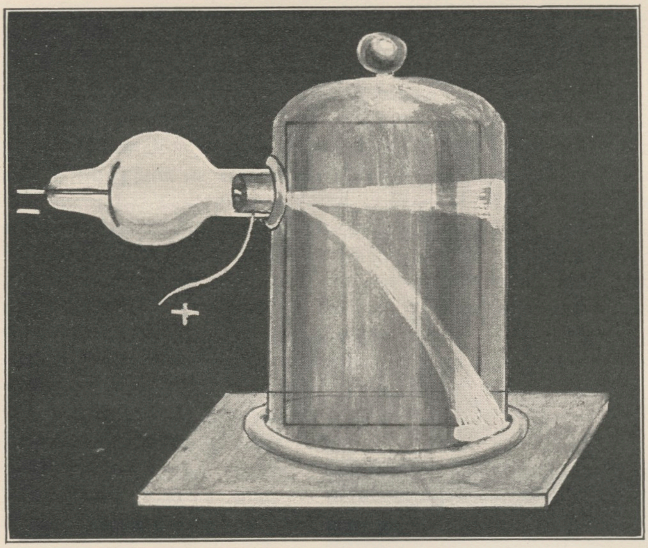

Fig. 7.—Showing Rays Deflected By Horseshoe Magnet

Matter in the corpuscular state is not confined to the cathode rays in an exhausted tube, for when a metal wire is made white hot in a good vacuum, matter in this state is given off. It is also given off when the metal, instead of being made red hot, is exposed to a bright light. In both these cases we get negative electricity in the gas round the wire; in fact, whenever we have negative electricity in a gas at a very low pressure, where there is very little matter in the ordinary state for it to stick to, we find the electricity is carried by the corpuscles. When the pressure of the gas is not low, the corpuscles get entangled with and ultimately adhere to the molecules of the gas, so that if we wish to get matter in this corpuscular state we must remove as much of the gas as we can; then we find that the negative electricity is always carried by these corpuscles, which are of the same kind however the electricity may have been produced.

The case is very different with positive electricity, for when the mass of the carriers of the positive electricity in a gas at a low pressure is measured, it is found to be the same as that of an ordinary molecule, and to depend upon the kind of gas in the tube; thus positive elec-

tricity is always found on matter in the ordinary state, while negative electricity is found on corpuscles. This difference between the two electricities is just that which ought to exist on the one-fluid theory of electricity due to Benjamin Franklin. According to that theory, electricity was supposed to be a fluid; when matter in the ordinary state contained a certain quantity of this fluid, it was said to be saturated, and not electrified; if some of the fluid left it so that it contained less than the normal quantity, it was charged with electricity of one sign; if some fluid came into it so that it contained more than the normal quantity, it was charged with electricity of the opposite sign. Now, if we suppose that the electric fluid consists of a collection of our corpuscles, the results of our experiments would be exactly expressed by Franklin's one-fluid theory, and it would thus seem that there is some warrant for the somewhat discredited "electric fluid."

If the material of the cathode rays forms negative electricity, it is evident that it must be very widely spread; we have seen that it occurs free near white-hot metals and metals exposed to the light.

We may suppose that it forms a part of all kinds of matter in the normal state, and that the heat and light which have to be applied to metals are only required to get the corpuscles out of the metal, and that in the metal itself, even under normal conditions, there are corpuscles moving freely about, and able to carry heat as well as electricity from one part of the metal to another. There are some substances which are perpetually emitting cathode rays without the need of any stimulus from heat or light. This, as has been shown by Becquerel, is the case with uranium and its compounds; the property is, however, possessed to an enormously greater extent by a new substance discovered by Professor and Madame Curie, and called by them radium, which is obtained from the mineral pitchblende. Its preparation is very difficult and laborious, as from several tons of pitchblende only a few grammes of radium can be obtained. This substance has been shown by its discoverers to emit corpuscles, and it is very remarkable that the velocity with which the corpuscles are emitted is about two-thirds of that of light, which is double the highest velocity we have hitherto been able to give (even with the most powerful induction coils) to the corpuscles in an exhausted tube. It is one of the romances of science that a harmless-looking white powder like radium should be perpetually bombarding its neighbors with projectiles of this velocity — a bombardment which is not always harmless, as I believe there are instances of sores being caused by too lavish an exposure to the radium attack.

Since corpuscles are emitted by hot metals, it seems not improbable that that very hot body, the sun, may be emitting corpuscles, some of which would strike the earth, where, stopped by the earth's atmosphere, and deflected by the earth's magnetic force, they would produce luminosity in the upper region of the earth's atmosphere, which they would make a conductor of electricity. The consequences of such a bombardment of the earth by corpuscles driven from the sun have been investigated by Paulsen, Birkeland, and especially by Arrhenius, who has shown that very many of the properties of the aurora borealis can be explained as the result of such a bombardment.

If this view is sustained by future investigations, we shall have to regard the corpuscles as playing an important part in cosmical as well as in terrestrial physics. The possibility of such a widespread scope for their action lends increased interest and importance to the investigation of their properties.

It is a striking instance of the unity of physical phenomena on the smallest and largest scale that an occurrence apparently so exceptional as the glowing of the glass in a small tube should be closely connected with some of the most widespread phenomena in nature, and give the clew to their explanation.